Flat Panel Detectors in Industrial Radiography

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1. INTRODUCTION

Real time imaging in the field of industrial radiography arrived over half a century ago and even before that in medical radiography. All the progress in the field for first 30 – 35 years produced analog images. Digital images have come only recently. Fluorescent screens, proximity focus intensifier and then electromagnetically focused Image Intensifier produced real time images in analog. They were viewed by analog video cameras. It was only in mid-eighties that the signal from those video camera devices (Vidicon, Isocon, Orthicon) could be digitized using a Frame Grabber cards. Though this may not be called `digital radiography' in a strict sense, the digital format entered the real time radiography (RTR) field for the first time by this route. It was then possible to modify the image, what we call `Image Processing' now. These operations were off-line initially as the cards digitized fairly slowly. Bandwidth of 5 MHz and above came later and image processing turned `near Real Time'.

Later, in mid-nineties we got detectors which produced output directly in digital form. In one of them, the phosphor Imaging Plate system, the process was analog but the read out itself was computer controlled and hence the output could be digital. Some call this computerized radiography (CR). The other was a family of detectors based on the semi-conductors. Before CCD and CMOS take root, the development in this technology quickly culminated into the flat panel detectors as they are called today. The technique using them is called the 'Digital Radiography' (DR) due to the digital output derived instead of a visual image.

2. BRIEF TECHNICAL HISTORY :

The idea of flat panel detectors has been partly derived from the LCD monitor screens of the Laptop computers. The system used for illuminating sequential pixels on LCD screen employs thin film transistor switches. They are arranged in a two dimensional array on a glass substrate. In a LCD monitor, an appropriate charge is sent to a pixel of interest, to make it glow at desired intensity; whereas for the flat panel application the reverse happens. If a pixel glows due to X-rays, one can arrange to get the proportional charge created and transferred to a reading device. This self scanning construction is called the `active matrix'. Before learning how charges are produced, it owes to history to mention the functioning of photodiode arrays, which are predecessors to this arrangement. They also use silicon based semiconductors. Use of semiconductors as photo-detectors or as a switch (in diode or transistors) for read out, started with photodiode arrays. Just as in solar photo voltaic, silicon gives hole-electron pairs under suitable construction and bias. A typical construction based on photodiodes is shown in Fig.1. On receiving the image photons the photodiode produces electrons and the field effect transistors (FETs) act as switches for the read out. The electronics for read out was elementary and gave pattern noise etc. By itself silicon is sensitive to optical light and low KV X-rays; but to make it useful at higher energies, a layer of X-ray sensitive scintillator is placed over the Si photodiode. Such systems came somewhat later and are in use even today by the name of Linear Diode Array (LDA), popularly used in baggage inspection and other such applications where resolution requirements are not of high order.

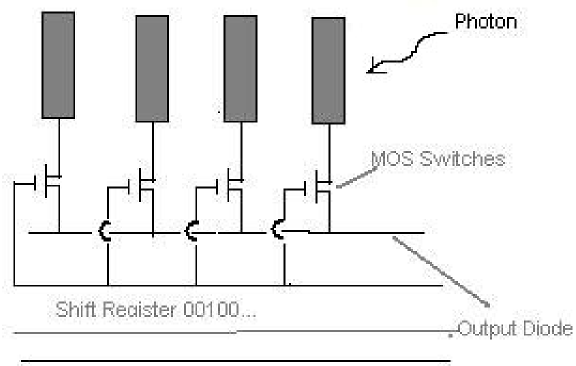

Fig 1. Typical construction of the photodiode array

Charge Coupled Devices (CCD) were next optical sensors used for X-ray detection by adding scintillator layer. Here the charges produced are moved out by shifting it to the next neighbour and from there to its neighbour and so on , just as a ball is passed in a game. Transfer of charges towards right side pixels is controlled by a shift register, which sends them out of array for final read out. But the technology then could not make large image sensors out of CCD bringing a quick end to the concept in RT field. CMOS also does the same job, of converting light into electrons, with a difference in read-out mechanism. Though invented for video camera, CMOS also coated with converter scentillator, were used in X-ray imaging. They were less expensive, used lesser power but were less sensitive also. Though they had small pixel size possible, overall dimension was the limitation; hence before they establish, a better option of flat panel detectors (FPDs) arrived. These can be much larger in size as compared to CCD and CMOS – an important requirement in medical radiology. They later entered industrial radiography, not long ago.

3. CONSTRUCTION OF FPD

A plan view of a typical flat panel detector looks as given in Fig.2. The entire structure is built on a glass substrate. The figure shows nine pixels but the pattern repeats for a matrix of hundreds of pixels. They are sequentially arranged in a row and there are number of such rows. Each row is connected through a line which is called a Gate line and columns are linked by `Data Lines' or `Drain lines'. Architecture of individual pixel is as given in Fig.3. The top layer converts x-rays into optical light. Most common phosphors used for this purpose are gadolinium oxysulphide (Gd_2O_2S – called GOS for short) and CsI. The light from phosphor falls on photodiode which creates charges proportional to light intensity. They get deposited on signal storage capacitors shown in the figure. All pixels have their own thin film transistor (TFT) made of amorphous silicon. TFTs play a specific role in read out of the charges, which are stored during the exposure. During the exposure these transistors are in `Off' mode and signals from pixels are stored as charges in capacitors available on each pixel. This is like a latent image in a charge form. For read out a positive pulse is given to the TFTs in Gate line 1. This permits data from all capacitors of the first line to flow to data lines D1, D2,…,.. Dn, Data reaches the charge amplifiers shown at the bottom for amplification and later digitization. All pixels in the first line are thus read and stored. During this period other Gates are closed and data remains on capacitors. Next, Gate 2 is opened to collect pixels in G2 line and so on. A charge erase cycle is applied at the end of read out to prepare the panel for next exposure. As the computer collects all digitized data, the name 'Digital RT' (or DR) is given to the method.

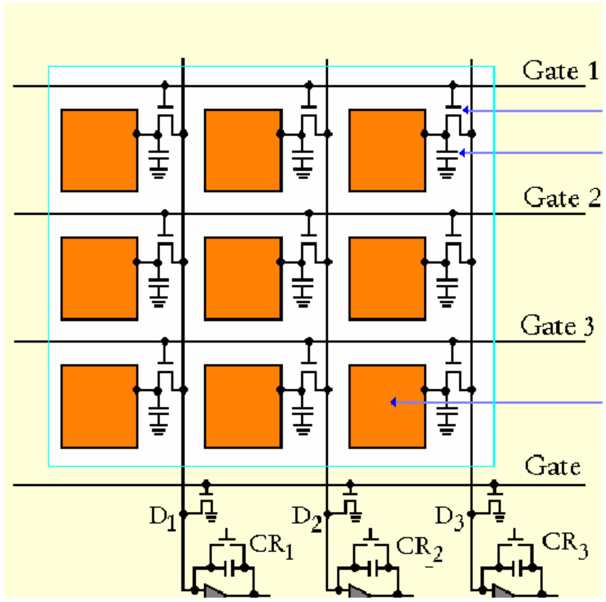

Fig 2. A small segment of Flat Panel Detector showing pixel layout

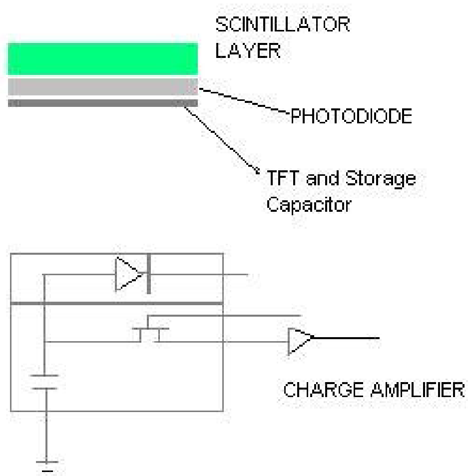

Fig 3. Structure of an individual pixel and its circuit representation

3.1 Properties of Converter Phosphors

Most of the electronic imaging devices for X-rays use scintillators at the entry surface to convert x-rays into visible light. Image intensifiers, linear diode array, x-ray vidicon and flat panels are the examples. These scintillators have some properties which become important in device performance.

a) Conversion Efficnecy
b) Nature of light output
c) Quenching time of phosphorescence (After glow)
d) Transparency to its own radiation

Presently, we will compare CsI and GOS which are used in the FPDs.

Conversion efficiency is the ability to produce light from incident x-rays. It depends upon the stopping power of the material and also the crystal structure. Stopping power is derived from atomic number of elements making the scintillator and specific gravity. GOS due to high atomic number is ahead in this but light conversion per x-ray photon is less; hence overall light output is better for CsI as compared to GOS. In **nature of light output**, mainly the wavelength is considered in view of the efficiency peak of photo cathode or photo diode. Usually above 500 nm wavelength is preferred. **Quenching time** of scintillation is determined by the decay time of the meta-state involved in transition. If decay takes longer than about 1–3 mSec, previous image lingers before new image comes, in the case of real time RT. This is considered unacceptable.

Though CsI is more **transparent to its glow**, in a new technique crystalline needles are grown which prevent transmission to neighbouring needles. Thus resolution in CsI is better when this kind of crystals (Fig. 4) are used. At higher energies, GOS is able to stop more photons in its volume and hence proves better than CsI which has lower efficiency. It also is cheaper than CsI layer as the coating technology is easier than growing needle crystals. The linearity is also better for GOS than CsI at higher energies.

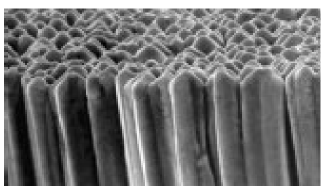

Fig 4. Scintillation crystals grown in needle shape

Table 1 : Properties of some materials useful in x-ray detection[1]

Material	Relative density	Atomic No.	Band Gap (ev)	Pair creation Energy (ev)	T_{90}
Semiconductors:					
amorph Si	2.3	14	1.7	4	23 mm
amorph – Se	4.3	34	2.3	40	1.39 mm
CdTe	6.2	48-52	1.44	4.42	66 μ
HgI_2	7.6	80-53	2.13	4.15	65 μ
PbI_2	6.2	82-53	2.32	14.8	64 μ
Converters:		Effective Atomic No.	Emission Peak	Emission Colour	
CsI:Na	4.5	54	420 nm	Blue	0.78 mm
Gd_2O_2S:Tb	7.3	59.5	545 nm	Green	1.15 mm

Note: T_{90} = thickness required to stop 90% photons of 50 keV energy

3.2 Direct Type Flat Panels

Figure 3 and subsequent discussion was based on the flat panel construction where x-rays were converted to light and then a photodiode followed. This `indirect' FPD construction was needed due to inefficient absorption of x-rays by silicon. But some materials like Selenium or CdTe have much better stopping power. Se also has photo conductive properties. That gave rise to direct type FPD structure as shown in Fig.5. Se layer of about 1mm thickness is the detector here. On absorption of x-ray energy, amorphous selenium produces charge pairs. No separate scintillator is required. Under the application of bias, electron and holes travel to respective electrodes. Further the construction is similar to indirect type i.e. a TFT and storage capacitor for each pixel is provided.

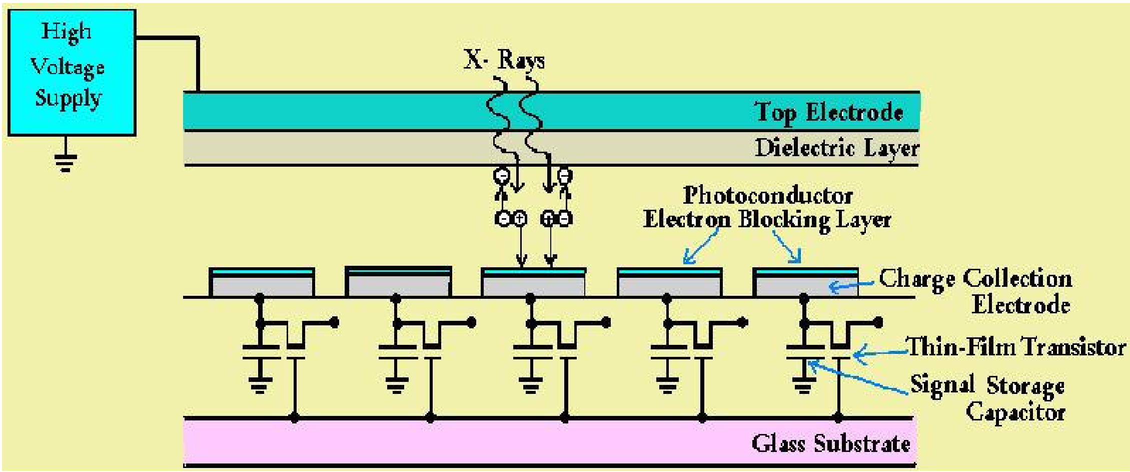

Fig.5 Structure of Direct type FPD using photoconductor layer of amorphous Selenium

As there is no scintillator (or phosphor), lateral spread of light is absent here. This is an important difference between direct and indirect construction. The resolution is governed by pixel geometry alone in the case of α-Se direct type FPD whereas in case of indirect set up it is worse than pixel size because of lateral light spread. α –Se has higher work function and hence less number of charge pairs are produced for a given energy; but it directly receives x-rays and hence overall conversion efficiency is better than tandem arrangement of scintillator & photodiode. This compensates to an extent for lesser charge pairs. However, Se has a limited stopping power and hence its applicability is upto about 100 – 150 kV of X-rays only. Beyond this energy Se layer thickness would become impractically thick. From this consideration, alternative materials like CdTe, HgI_2 and PbI_2 are being explored as they have better stopping power as can be seen from the Table. (see $T_{9}o$ values in Table 1).

4. PERFORMANCE OF FPD AS AN IMAGING DEVICE

FPD is a new concept in instrumentation related to imaging. Therefore, its performance could be studied from two angles.

(a) characteristics of the hardware
(b) quality of the image obtained

Both these will be reviewed shortly. Prior to that an important step of calibration of the device must be visited.

4.1 Need for a Calibration

An average FPD consists of at least a million pixels. Each pixel has a layer of scintillator and semiconductor diode on itself as well as a transistor built *in situ*. It is expected that there will be statistical variations in overall charge output due to manufacturing variations and leakage current etc. To get a uniform output faithfully proportional to incident x-ray flux, a process of calibration is undertaken before delivery. This also improves signal to noise ratio and contrast sensitivity. In this, each pixel is addressed for the gain and offset (i.e. when no x-rays are incident). The full detector image is gathered with no exposure, thereby creating a dark-current image. Similar image is gathered at parameters most likely to be used. Gain of each pixel and variation in charge amplifier output are noted here and a Look Up Table

(LUT) is created for correction to be applied in actual use so that there is consistency in output between exposures. Amplifiers are tuned to obtain uniform output. Ideally, the calibration should be redone if different exposure conditions are used. Also, this procedure needs to be repeated periodically every few years to ensure consistency. However, it is not scrupulously done because there is a chance of many pixels going bad over the years and the process of calibration will only go more complex with known defaulter pixels. To this extent it is anticipated that the performance of an FPD will deteriorate with time or radiation dose and this feature is similar to what is observed in image intensifier system, though the underlying reasons may be different.

4.2 Properties of Hardware

There are certain quality parameters inherent to the device. They are discussed here.

(i) Speed : As the device works on semi-conductors, it needs very low dose for image formation. They are 30 to 50 times faster than film, as per the type of construction.

(ii) Fill factor : The pixel size of any kind of FPDs currently is 120 to 130 μ. But the entire area of any pixel is not sensitive to radiation. Hence the sum of the sensitive pixel area does not add upto the total physical area of the detector. As can be seen in the Fig.6, there is some dead area which is used to accommodate circuit elements. This ratio of active area (sensitive area) to total area is called the `fill factor'. This is an aspect unique to FPDs. Although the image on TV monitor will look continuous, the image (as obtained) will have small gaps in between pixels. Thus, higher the fill factor better is the resolution. Typical fill factors are as given here :

Gd_2O_2S phosphor on α-Si : 55 to 58%
CSI needle crystals on α-Si : 70%
Direct type FPD of α-Se : 85%

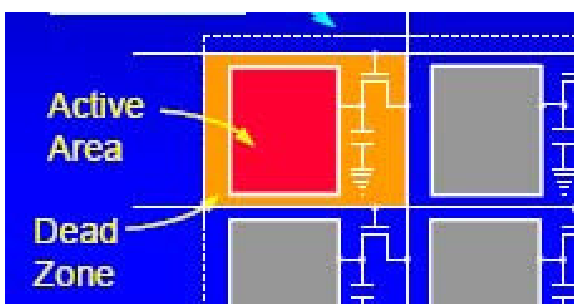

Fig 6. The Concept of Fill Factor

(iii) Dynamic Range and linearity
Flat panels have a dynamic range of at least 4 orders i.e. 10^4. This is much higher than films and reaching close to image plates. Linearity of grey level and exposure is also there. In the case of CsI there may be some deviation in linearity w.r.t. energy, but that is not an issue in imaging application.

(iv) Other features
Apart from a definite life, there are a couple of other limiting features, particularly applicable to selenium based FPD. They are temperature sensitivity and Lag.

α-Se is unstable beyond 30˚C and hence its use has to be in an air-conditioned lab. It also has slow re-set and the image does not fade fast, thus making it unsuitable for real time application where the object is moving. Such ghost artefacts make it unsuitable for automatic defect recognition (ADR) process also.

All the versions of FPD have one significant advantage over the image intensifier based system and that is an absence of blooming. The CCD cameras used with I.I. system have a read out mechanism which essentially passes the charge to the neighbour, till the charge reaches the end of line. Thus an excessive charge at a point (where the image is bright) floods the neighbour pixels and the entire scene brightens up in a flash; this is called blooming. In FPD, as we know, the read out deals with each pixel independently and charge drain is also available on each pixel; hence a blooming is ruled out. This is an important benefit.

5. QUALITY OF OBTAINED IMAGES

Any image can be evaluated with respect to three main parameters viz.
Contrast
Definition (or Resolution)
Noise.

These parameters are affected by many factors and the detector is one of them. Not much work has been done using FPD detectors and hence the discussion in the ensuing section will be for particular varieties of FPDs, for which the data was available.

5.1 Resolution and Contrast

Flat Panels entered the imaging field for medical application where speed (i.e. the low patient dose) was the primary consideration. Till mammography applications became frequent, resolution was not considered so important. As the FPDs have pixel size of 120 to 130μ as of date, it sets the limit of resolution. However, it can be used in magnification mode (if focal spot permits) to achieve better `virtual' resolution. Subject contrast obtained by a-Se type FPD is shown in Fig.7(a) and (b) respectively for aluminium and steel objects[2]. The slope of lines indicate contrast. As can be expected, 50 KV gives better contrast than 100 KV (for Al) and 100 KV better than 200 KV for steel.

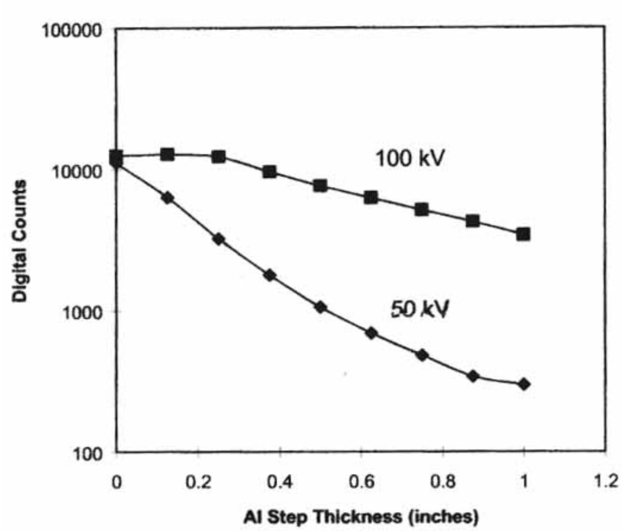

Fig 7(a) Subject Contrast obtained with a-Se FPD in Aluminium

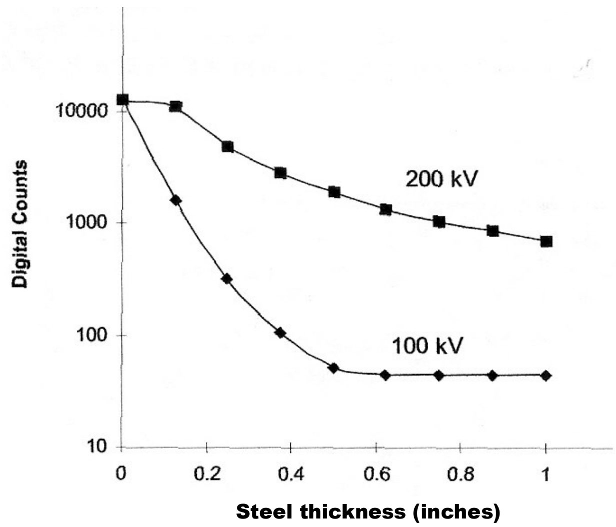

Fig 7(b). Subject Contrast in Steel using a-Se detector

This was a simple case of step wedge. However, it is difficult to ascertain psycho-visual aspect of contrast in a real life specimen because the FPD device is operated inherently by computers and therefore every time the contrast is manipulated artificially. Therefore, better parameter to study will be contrast transfer rather than absolute contrast. Contrast transfer factor (ratio of output to input contrast) is represented by Modulation Transfer Function - MTF. It gives information about device's behaviour in relation to spatial frequency. Thus it informs us about contrast and resolution simultaneously and their interdependence.

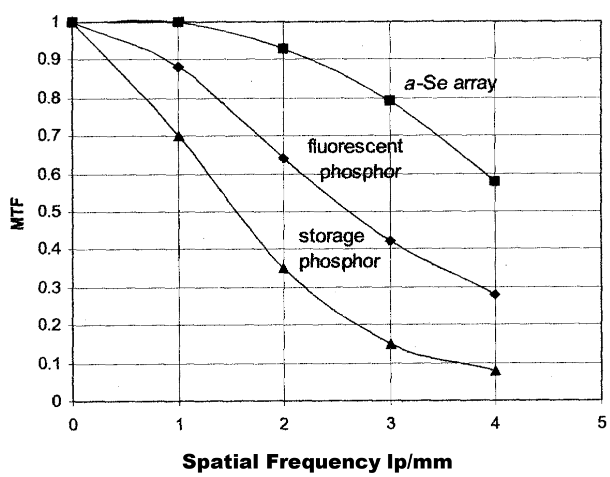

Fig 8. Comparison of MTF of different imaging devices

Soltani et al [(2)] have given curves comparing MTF for α-Se array and CR plate (Fig.8). At 3 lp/mm MTF is 80%, which is very good behaviour. However FPD using CsI and GOS are not as good. Casagrande[(3)] obtained MTF curve for GOS at 60 kV wherein the transfer factor is only 30% at 3 lp/mm- far less than α-Se in Fig.8. Fig.9 a & b, show MTF curves obtained at 100 kV x-rays and Ir192 energies. Here, Willems et al [(4)] have compared two indirect type FPDs (GOS and CsI) and one direct (α-Se) with Image Plate (CR) and film. Two things clearly emerge here :

(i) α-Se device (with 220 mg/cm^2 layer) is far ahead of all others (except film), for all energies.

(ii) CsI (thicker layer – 200 mg/cm^2) and GOS (70 mg/cm^2) are nearly similar and comparable with CR. The MTF is only 20% at 2.5 lp/mm frequency. This is lesser than that achieved by Casagrande in ref (3) for device with GOS phosphor; difference can be due to their panels or because the previous result is at lower kV.

New materials PbI and HgI_2 have shown much better MTF curves in laboratories. They have yet to reach the shop-floors.

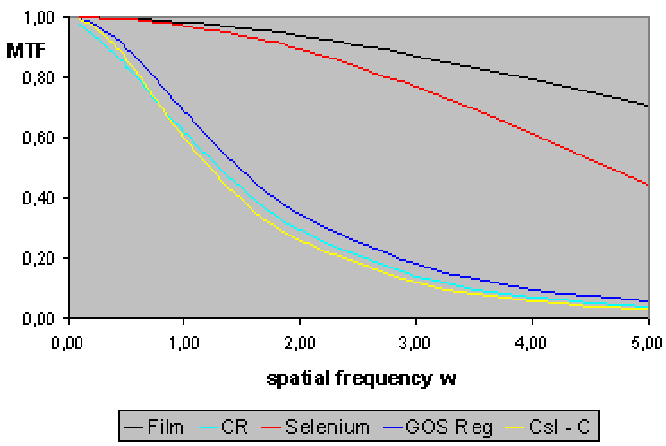

Fig 9(a). Comparison of MTF of Film ,CR and DR systems at 100kV x-ray energy

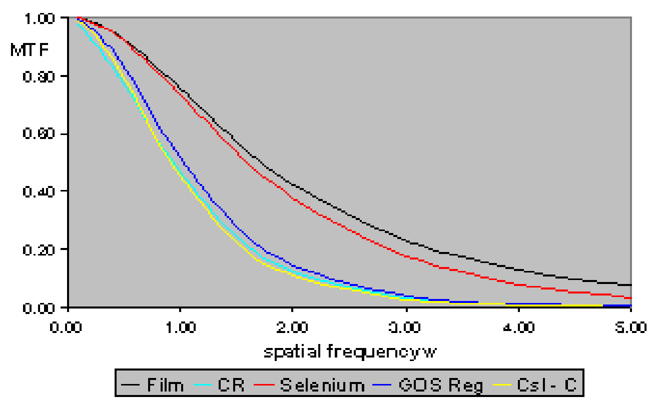

Fig 9(b). Comparison of MTF of Film ,CR and DR systems at Ir-192 energy

5.2 Noise & DQE

Noise in any image can suppress the fine details and thus affect resolution. In X-ray detection, noise can come due to statistical variation in the source of radiation or due to electronic noise from the detection device itself. A simple measure of noise is signal to noise ratio (SNR). However, this is more suitable in electrical and electronic field and less in imaging field. There is one more parameter called Detective Quantum Efficiency (DQE) which is defined as

$$DQE = \frac{(\text{SNR in output image})^2}{(\text{SNR in input image})^2}$$

Just as MTF quantifies contrast transfer properties, DQE quantifies noise transfer properties from input to output. However, being based on SNR for which measurements are difficult, DQE also is difficult to find experimentally. Various authors have approached it theoretically; one of them Willems *et al* have even compared various detectors with radiographic films[4]. These results are given in Fig.10. DQE is a frequency dependant parameter. Fig 10(a) gives such behaviour for one variety of each detector. It shows that DQE for direct type (a-Se) FPD is lesser than indirect FPD CsI or GOS phosphors of a particular layer thickness. But at higher frequency the difference reduces or vanishes. In Fig 10(b) values at zero frequency DQE(0) are given for different grades of each kind of detector. CsI–C is a thicker layer and hence faster than B or A variety. They have shown that a-Se is better compared to thin layer of phosphors viz. CsI-A (having 50 mg/cm^2) and GOS-fine with 34 mg/cm^2 coating thickness.

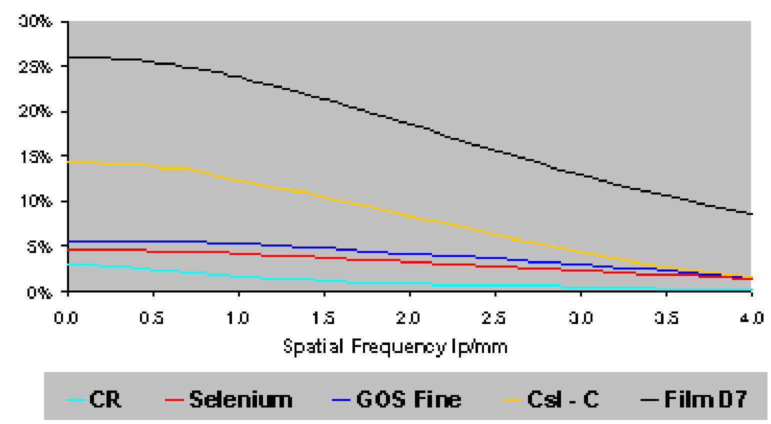

Fig 10(a). DQE(w) for various detectors and film

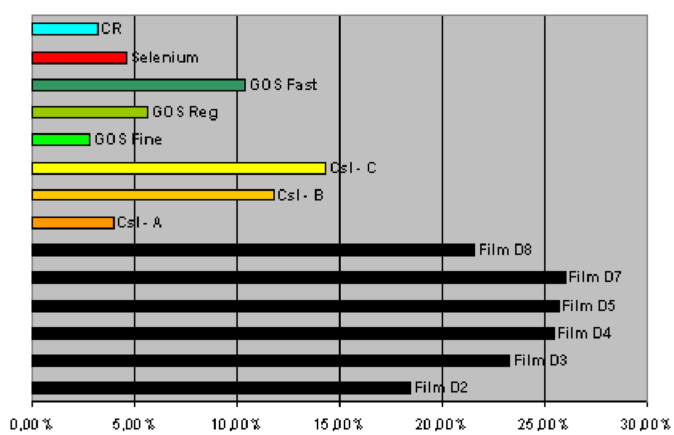

Fig 10(b). DQE (0) for films and various detectors

5.3 IQI Sensitivity

In absence of universally adopted DQE measurement, it looks prudent to assess the effect of noise by penetrameter visibility only. For radiography field that is a direct test of any detector and indicates contrast also. Performance of flat panel detectors is gradually improving and with the assistance from image processing it has come quite close to films. IQI 2 – 2T and 2 – 1T in certain cases are now detected in usual materials like aluminium, steel, titanium etc. Soltani[2] has shown Equivalent Sensitivity (EPS) as good as 1.2% on 25 mm steel at 200 KV. With the help of equipment suppliers we have been able to show 0.2

mm pore on 14 mm SS cylindrical object which also works out to be 1.5%. But it needs quite a good effort in masking, compensating and image processing for achieving this.

5.4 Probability of Detection Study

Effectiveness of FPD in detecting simulated defects on weld was extensively studied by Bill Meade et al from Boeing Aircraft Co.[5], using FPD from Thales (127 μ) along with microfocus X-ray unit they inspected 40 welds in inconel (0.078" wall, 4" dia.) having 72 EDM notches of varying depths and lengths. Persons with Level 2 qualification made interpretation on these randomly positioned notches. The result is that 0.008" (200 μ) deep notch could be detected with 95% probability and 25 μ deep notch was seen with 20% probability. For length, probable detection was 95% for longer than 0.020" notches. It can be seen that the results using films could not have been much different.

FPDs have been used on welds, castings, honeycombs as well as for finding internal structures. Fig.11 and 12 give some images obtained by FPD to demonstrate the variety of objects it can test and defects detected. Lack of penetration, crack and fine porosities are comfortably seen in the pictures shown here, with adequate IQI sensitivity.

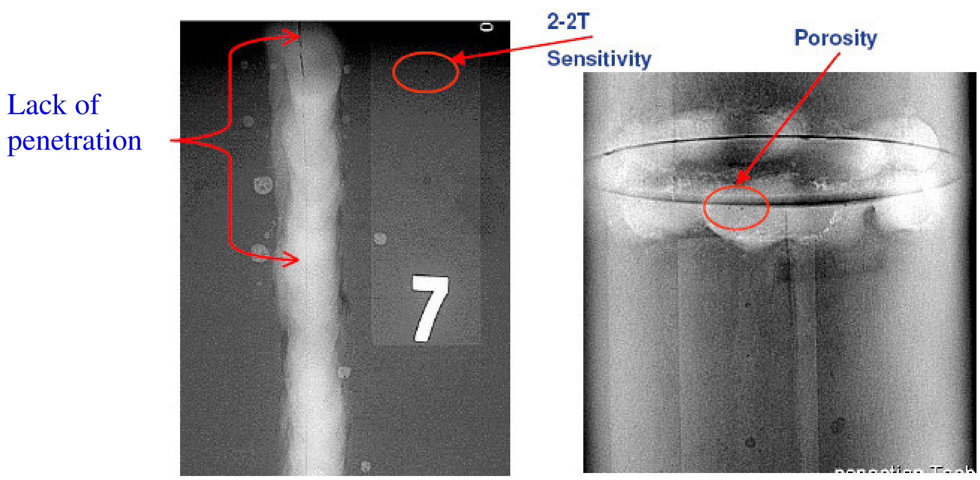

Fig 11. Weld radiography Images taken by indirect type FPD
(Pictures courtesy GE India Technology Centre , Bangalore, India)

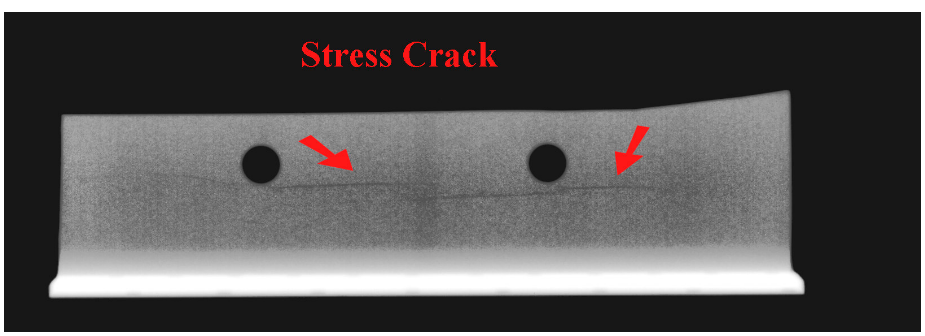

Fig 12. A sample of Aluminium wing with a stress crack
(Picture courtesy m/s VIDISCO Systems)

These detectors are also useful for 3D (cone beam) tomography as the area detector. Unfavourable factors are the price, life and the dead pixel problem. The savings in film cost can not compensate for the investment in these detectors unless someone has very large consumption of films. Till the prices become competitive they will remain only good laboratory tools. The problem of dead pixel currently can be addressed by software, wherein those pixels are not seen as black spots but are given dummy grey value similar to their neighbours. But this is only circumventing the problem, not solving it. Similarly the data is too less to decide the life-span of both the types of detectors.

SUMMARY

Historical developments leading to flat panels as near Real Time Detectors was retraced. It is shown that the Digital Format could be obtained with the Active Matrix base detector easily and larger area. Construction of direct type and indirect type flat panel detectors (FPD) were explained with functioning. Quality of image obtained by these was evaluated w.r.t different attributes with the help of published data. Characteristics like MTF and DQE were compared with film and other detection modes. Finally examples of field use were given.

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